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14. ABSTRACT
High-resolution numerical simulations of the Korean Straits and East Sea utilizing the Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS®), the Navy Coastal Ocean Model (NCOM), and the SWAN wave model are conducted to examine the ocean and atmosphere model skill and response to Typhoon Maemi (September 2003). Due to the rarity of an intense tropical cyclone making landfall on the Korean Peninsula and traversing through the East China Sea, this study attempts to model the ocean and wave response to these types of events in this region. Nested grids of 27, 9, and 3 km for COAMPS®), 2 km NCOM, and 2 km for SWAN, provide realistic coastal mesoscale simulations to compare to observational atmospheric and ocean data where applicable. Two-way coupling of COAMPS® and NCOM will be investigated to assess viability with regards to tropical cyclones.

15. SUBJECT TERMS
Typhoon Maemi, COAMPS, upper-ocean response

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7A.5 HIGH-RESOLUTION NUMERICAL ATMOSPHERIC AND OCEAN SIMULATIONS OF TYPHOON MAEMI (SEPTEMBER 2003)

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1. INTRODUCTION

The recent devastation caused by several tropical cyclones (Katrina and Rita (2005), Sidr (2007), Nargis (2008), Ike (2008)) has highlighted the importance of continual improvements in tropical cyclone intensity, track, wave, and storm surge modeling. The primary focus of this study involves the wave and ocean response to Typhoon Maemi in September 2003 which made landfall as an unusually intense typhoon along the southern coast of South Korea. The storm surge produced by the typhoon severely damaged several port cities along the coast and brought high wave action into the East Sea/Sea of Japan adjacent to the Korean Peninsula. For Typhoon Maemi, model results from COAMPS, NCOM, and SWAN are utilized to explore the upper-ocean response to this quickly moving storm over the Korean Straits and East Sea/ Sea of Japan. Each stand alone model is investigated for accuracy based on in-situ, satellite, and best-track data provided by several agencies. However, increased emphasis on coupled atmospheric and ocean modeling involving tropical cyclones is important and necessary to understanding the physical wave and ocean response to extreme wind stresses and their impact on coastal regions.

2. BACKGROUND

Super Typhoon Maemi (5 SEP – 13 SEP 2003) developed in the western Pacific near Guam on 5 SEP. Maemi steadily intensified until 9 SEP when it intensified rapidly and reached a peak intensity of 150 kts on 10 SEP. Maemi began to weaken as the typhoon headed northward around the periphery of the subtropical ridge in the western Pacific, and made landfall on the southern coast of South Korea as a category 2 (SSHS) typhoon at approximately 12 UTC 12 SEP. Maemi was the most intense typhoon to make landfall on the Korean Peninsula since 1959.

There are several important factors to consider in the rapid intensification and subsequent maintenance of intensity until Typhoon Maemi's landfall. First, the typhoon traversed several warm core eddies well to the south of the Korean Peninsula (south of 20°N) which has been studied and documented by several investigators (e.g. Lin et al. (2005)). They concluded that the deep warm water eddies were a primary factor in the rapid intensification of Maemi. Secondly, the SST distribution to the south of the Korean peninsula played a significant role in maintaining the intensity of the typhoon until landfall. Generally, as a typhoon approaches the Korean peninsula from the south, a combination of increased upper-tropospheric wind shear and rapidly decreasing oceanic heat content induces weakening. For the special case of typhoon Maemi, SSTs south of the Korean peninsula were approximately 2°C above average for the week before Maemi approached. The combination of an intense tropical cyclone traversing warmer than average SST led to a much stronger typhoon at landfall in South Korea than would be expected. Maemi rapidly weakened after landfall and transitioned to an extratropical cyclone over the East Sea/Sea of Japan, but not before producing some strong winds and wave action over the East Sea.

3. MODEL DESCRIPTIONS

We conduct simulations of Typhoon Maemi using the Navy Coastal Ocean Model (NCOM). NCOM is a hybrid sigma/z-level primitive equation, free-surface model invoking the hydrostatic, incompressible, and Boussinesq approximations (Martin, 2000).

Surface forcing is provided by the atmospheric component of the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) (Hodur, 1997). The COAMPS atmospheric model is fully compressible, non-hydrostatic, and uses

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parameterization schemes for subgrid-scale convection, shortwave and long-wave radiation processes, and mixed-phase cloud microphysics. The COAMPS system was run in hindcast mode and contains three-dimensional multivariate optimum interpolation (MVOI) analysis technique to generate the initial conditions for the COAMPS model in each data assimilation cycle. In this step, quality-controlled data from radiosondes, aircraft, satellites, and surface observations are used to create an MVOI of winds and pressure heights, while a univariate OI is performed for temperature and moisture.

The COAMPS Maemi configuration is a triply nested (27, 9, 3 km) domain where nest 3 constitutes a portion of the East Sea adjacent to the Korean Peninsula. This region is investigated at higher resolution due to the rarity of an intense tropical cyclone traversing these waters. The 9-km nest includes the entire region surrounding the Korean Peninsula, including the Korean Straits and almost all of the Sea of Japan/East Sea. At 00 UTC and 12 UTC of each day a data assimilation cycle is initiated using the prior 12-h forecast as the first guess. Atmospheric boundary conditions are provided by NOGAPS data. The model is run 15 days before the primary investigation date to allow for proper spin-up.

The ocean model NCOM was configured to cover the entire region surrounding the Korean Peninsula (6-km resolution) with 2-km horizontal resolution in the region specified by COAMPS nest 3. NCOM boundary conditions are provided by global NCOM data. NCOM simulations include tides from the Oregon State University regional tidal database (Egbert and Erofeeva, 2002) and monthly river discharge.

The SWAN (Simulating Waves Nearshore) model is a third-generation numerical wave model that computes random, short-crested waves in coastal regions with shallow water and ambient currents (Booij et al., 1999). The model is based on an Eulerian formulation of the discrete spectral balance of action density that accounts for refractive propagation over arbitrary bathymetry and current fields. It is driven by boundary conditions and local winds forced by COAMPS output. Outputs from the model include significant and maximum wave height, mean wave direction, mean wave period, peak wave period, and peak wave direction.

4. COAMPS MODEL RESULTS

Typhoon Maemi's landfall occurred at approximately 12 UTC on 12 SEP near the port city of Masan, South Korea. As the typhoon traversed the Korean Straits a few observations collected from several sites show that the mean sea level pressures (MSLP) at these sites computed by COAMPS were off by approximately 10 hPa. Observations at 7 UTC, at the time of closest approach at Cheju, South Korea, (located on the large island south of the Korean Peninsula) indicated a MSLP of 975 hPa and winds of 24.7 m s^{-1}. COAMPS resulted in a pressure of 989 hPa and winds of 18.5 m s^{-1} at Cheju. Observations at 10 UTC (at the last available time) at Tsushima, Japan (located on an island in the Korean Straits) indicated a MSLP of 990 hPa and wind speed of 21.1 m s^{-1}. The large pressure discrepancy is attributable to the NOGAPS boundary conditions having higher pressures than observed for the typhoon. Although improvements are currently being made, many atmospheric models typically do not capture the intensity of strong tropical cyclones because they are unable to resolve the inner core structure of the typhoon well; however, COAMPS was able to improve on the existing NOGAPS boundary conditions by several hPa.

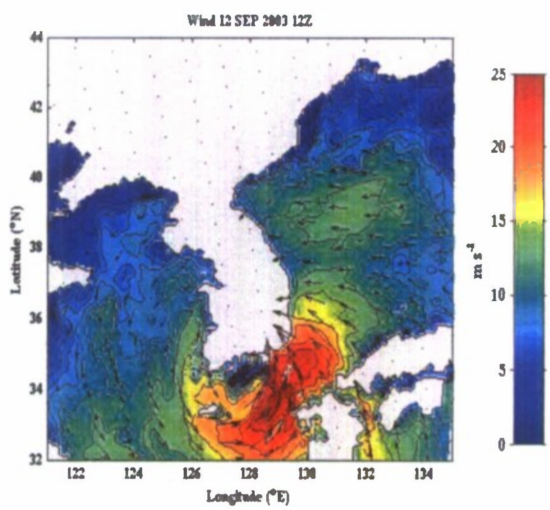

Figure 1: COAMPS wind (m s^{-1}) and wind vector output for 12 UTC SEP 12 indicating landfall of Typhoon Maemi near Masan,South Korea.

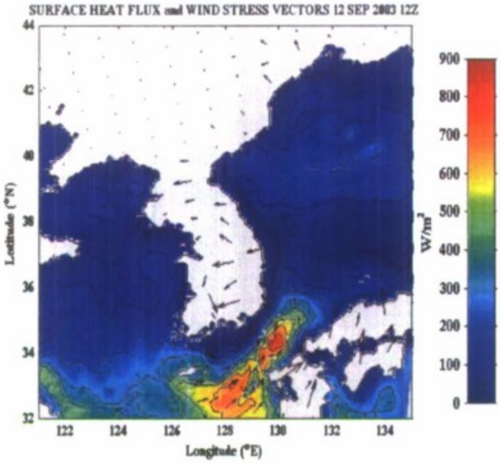

Figure 2: COAMPS surface heat flux and wind stress vectors for 12 UTC SEP 12.

The overall wind structure of the typhoon at 9-km resolution is captured well due to the assimilated data. The strongest wind and wind stresses (Fig. 1) are located just to the right of the eye consistent with a typhoon that is quickly translating to the NNE (12 m s^{-1} for Maemi). The total surface heat flux associated with the wind stress is consistent as well (Fig. 2). At 9-km resolution there is also evidence of spiral banding in the wind field which is difficult to validate due to the lack of observational data in this region. As the typhoon emerges off the Korean Peninsula, the cyclone quickly begins to undergo extratropical transition; however strong winds (approximately 20 m s^{-1}) are present in the high-resolution 3-km COAMPS grid that is located just to the east of North Korea (Fig. 3). A buoy located just off the coast of northern South Korea near the southern edge of the 3-km grid recorded maximum winds of 21 m s^{-1} at approximately 18Z on 12 SEP as the eye passed just to the east of the buoy. This atmospheric observation agrees well with the COAMPS produced wind speeds. Again, it is important to note that Maemi was the strongest tropical cyclone to pass through the region indicated in the 3-km COAMPS grid in many decades.

5. UPPER OCEAN RESPONSE TO TYPHOON MAEMI AND NCOM MODEL RESULTS

To determine the relative importance of various processes in the upper-ocean response to tropical cyclones, several preliminary scale analyses and parameters are calculated from

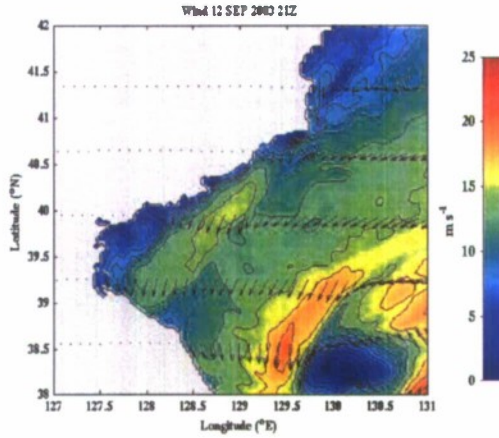

Figure 3: COAMPS 3 km resolution wind and wind vectors output for 21 UTC SEP 12. The center of Maemi is located in the lower-right hand corner translating to the northeast.

model data for Typhoon Maemi (Table 1). Derivation of most of these parameters can be found in Price (1983) and Price et al. (1994). These parameters quantifying the upper-ocean response to tropical cyclone passage have been found useful in past and current studies (e.g. Shay and Uhlhorn, in press, 2008).

To aid in the interpretation of the scaling parameters, it is important to note several key facts. The Korean Straits are shallow waters with maximum depths between 100 and 150 m that connect the broad, shallow East China Sea (depths between 50 and 1000 m) with the much deeper Sea of Japan (depths exceeding 2000 m). The major current features in the straitare the warm Tsushima Current, originating from the Kuroshio and Taiwan Warm Current (Nitani, 1972; Beardsley et al., 1985; Fang et al., 1991), and inflowing from the East China Sea and out flowing into the Japan East Sea. This configuration sets up a large SST gradient between the Korean Straits and Japan East Sea, which before the passage of Maemi, was characterized by much above average SSTs.

From the parameters calculated in Table 1, the upper-ocean response to Maemi would correspond to a quick moving typhoon over shallow waters. However, due to the large size of Maemi (i.e. the radius of maximum winds extended to about 85-90 km), some of the response would be expected to differ compared

to a tropical cyclone with a average radius of maximum winds (15-30 km) from the center of circulation. The mixed layer depth in the Korean Straits is approximately 20-30 m while the thermocline thickness is approximately 50-60 m. Dynamical effects that would have occurred over deep ocean depths due to a quickly moving typhoon would more than likely not have the same effects over shallow waters. For instance, the maximum wind stress based on COAMPS results using a standard bulk wind stress formula is approximately 1.7 N m^{-2}. The scaling of isopycnal displacements based on maximum wind stress and translational speed is only 1.63 m which is very small. The NCOM model results show that thorough mixing should still occur in the mixed layer depth as shown in (Figure 4). This figure indicates that near the area of maximum wind stresses the mixed layer depth temperature still decreased approximately 3-4°C from 00 UTC SEP 12 to 00 UTC SEP 13 after the passage of Maemi while the thermocline thickness also decreased due to mixing. On that note, careful considerations must be taken with each scaling parameter based on whether the ocean is deep or shallow. Other dimensional scales, such as wind-driven velocity, were accurately predicted by NCOM. The maximum NCOM value of the surface current was approximately 2.5 m s^{-1} which compares well to the scaled value predicted by the COAMPS results.

Other parameters are representative of a quickly moving typhoon such as the non-dimensional storm speed, S, which provides an indication of the timescale over which the ocean experiences the typhoon's wind stress and is relevant to generated inertial motion. The position of maximum SST cooling is usually observed to be displaced to the right of the path of tropical cyclones. This is primarily due to the clockwise wind stress vector rotation on the right side of the cyclone track. This effect is most likely to occur when S is O(1) which Maemi possessed. Figure 5 indicates the NCOM SST differences from 00 UTC 12 SEP and 12 UTC 13 SEP showing significant SST cooling to the right of the eye along the immediate shelf waters along the South Korean coast. Cooling elsewhere ranges from 1-2°C to the right of the eye which is typical of a fast-moving cyclone.

Even though the Froude number, which is a parameter related to upwelling, is large and indicative of very little upwelling, the shallow waters are mixed thoroughly through the wind

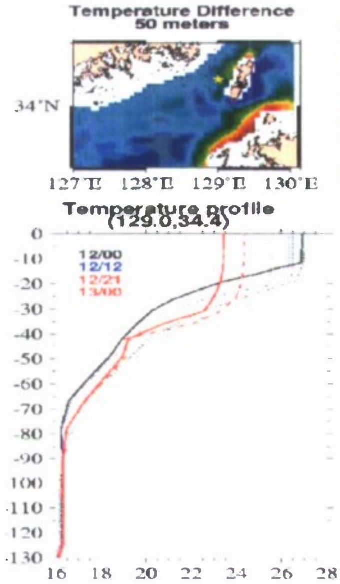

Figure 4: NCOM 50 m temperature difference (top) and temperature profiles (bottom) for point indicated by yellow star. Temperature profiles span 00 UTC SEP 12 to 00 UTC SEP 13.

stresses and cool significantly along the coast. A warm eddy just to the east of the Korean Peninsula is shown by NCOM to wrap the cooler surface shelf waters into the vortex. A Froude number less than 1 is indicative of large amounts of possible upwelling. The small Rossby and Burger numbers for Maemi are indicative of small nonlocal or advective effects during the forcing and early decay stages, and the small amount of pressure coupling between the mixed-layer current and the thermocline current, respectively. The large translational speed and large maximum radius of winds are responsible for the small Rossby and Burger numbers.

Parameter		Maemi
Radius of maximum winds (km)	R_{max}	86
Maximum wind (m s^{-1})	W_{max}	25
Maximum wind stress (N m^{-2} or Pa)	τ_{max}	1.67
Typhoon translational speed (m s^{-1})	U_h	12.0
First mode phase speed (m s^{-1})	c_1	~2
Inertial Period (days)	IP	0.88
Inertial Wave Length (km)	λ	38
Reduced gravity (m s^{-2} × 10^{-2})	g'	2.5
Mixed Layer Depth (m)	h	20

Themocline Layer Thickness (m)	b	50
Non-Dimensional Parameters		
Froude number (Fr)	$\frac{U_h}{c_1}$	~6.0
Nondimensional storm speed (S)	$\frac{\pi U_h}{4 f R_{\max}}$	1.31
Mixed Layer Burger Number (M)	$\frac{g' h}{(2R_{\max} f)^2}$	0.006
Thermocline Burger Number (T)	$\frac{b}{h} M$	0.015
Rossby number (Ro)	$\frac{\tau}{\rho_o h U_h f}$	0.08
Dimensional Scales		
Wind-Driven Velocity $(V_{ml} : m\ s^{-1})$	$\frac{2\pi R_{\max}}{\rho_o h U_h}$	2.2
Thermocline Velocity $(V_{th} : m\ s^{-1})$	$\frac{h}{b} V_{ml}$	0.88
Isopycnal Displacements $(\eta_s : m)$	$\frac{\tau_{\max}}{\rho_o f U_h}$	1.6
Geostrophic Velocity $(V_{gs} : m\ s^{-1})$	$\frac{g' \eta_s}{f R_{\max}}$	0.57

Table 1: Dimensional and nondimensional parameters (Price (1983, 1994), Shay and Uhlhorn (in press, 2008)) for Typhoon Maemi as the storm approached the Korean Straits (from COAMPS and NCOM model data).

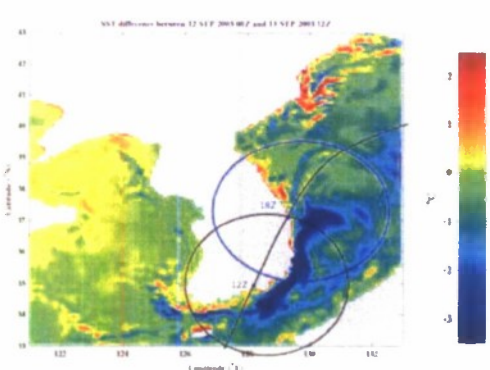

Figure 5: NCOM output depicting the SST difference between 00 UTC 12 SEP 2003 and 12 UTC 13 SEP 2003. The track of Typhoon Maemi and the 34 kt wind radii are shown.

6. SWAN MODEL RESULTS

Utilizing the results from COAMPS, the SWAN model is run for the 3-km grid shown in Figure 6 for the 12-hour period beginning at 18 UTC SEP 12. The SWAN model outputs wave quantities such as significant wave height, and the resolution of the SWAN grid is 0.02°. As the center of Maemi passed through the lower right-hand corner of the grid, the significant wave heights increased to slightly more than 4 m in height (Fig. 6). Buoy observations (Fig. 7) just off the northern South Korean coast recorded significant wave heights near 4 m as the center of Maemi passed offshore providing some validation of the SWAN results.

7. REVIEW

A suite of models are used to analyze the effects of Typhoon Maemi in a region that scarcely experiences such a strong tropical cyclone. Although the MSLP and winds were weaker than observations as the typhoon made landfall, the COAMPS model with assimilated data was accurate with regards to the cyclone's structure, region of maximum wind and wind stresses, and cyclone track. NCOM provided guidance with regard to the expected upper-ocean response after the passage of Maemi in the shallow waters of the Korean Straits, and these results were compared to scaling parameters derived by Price (1983) and Price et al. (2004). Careful considerations of the scaling parameters must be made for an accurate depiction of the upper-ocean response in relatively shallow waters. Also, the SWAN model produced wave heights that compared well with buoy observations which provided some validation.

Figure 6: Significant wave height (m) data output by SWAN.

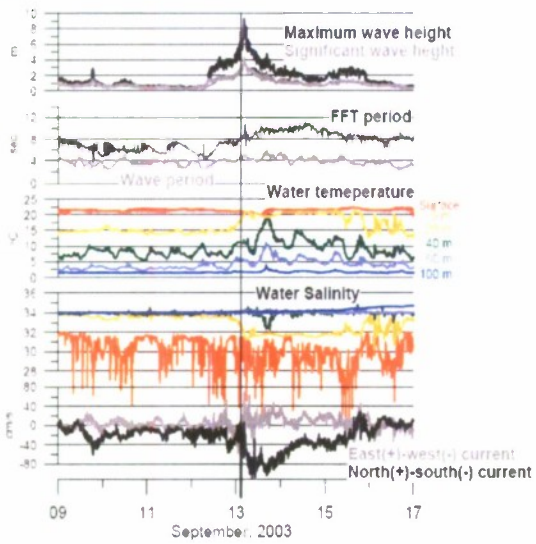

Figure 7: Ocean observations from the East Sea Real-Time Ocean Buoy (ESROB) that is located 9 km offshore from Donghae, South Korea. SOURCE: Kim et al. (2004), Real-Time Wave Measurement Using an Ocean Monitoring Buoy, Workshop on Wave, Tide Observations and Modeling in the Asian-Pacific Region, 2004.

8. REFERENCES

Beardsley, R. C., R. Limeburner, H. Yu, and G. A. Cannon, 1985: Discharge of the Changjiang (Yangtze River) into the East China Sea. Continental Shelf Research, **4**, 57-76.

Booji, N., R. C. Ris, and C. H. Holthuijsen, 1999. A third generation wave model for coastal regions, Part I, Model description and validation. J. Geoph. Res., 104, C4, 7649-7666.

Egbert G. D. and S.Y. Erofeeva, 2002: Efficient Inverse Modeling of Barotropic Ocean Tide, J. Atmos. Ocean Technol., 19(2), 183-204.

Fang, G., B. Zhao, and Y. Zhu, 1991: Water volume transport through the Taiwan Strait and the continental shelf of the East China Sea measured with current meters, Pp. 345-358 in Oceanography of Asian Marginal Seas, K. Takano, ed. Elsevier, Amsterdam, The Netherlands.

Hodur, R. M., 1997: The Naval Research Laboratory's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS), *Mon. Wea. Rev.*, **125**, 1414-1430.

Lin I., C. Wu, K. Emanuel, I. Lee, C. Wu, and I. Pun, 2005: The interaction of Supertyphoon Maemi (2003) with a warm ocean eddy, *Mon. Wea. Rev.*, **133**, 2635-2649.

Martin, P. J. (2000), A description of the Navy Coastal Ocean Model version 1.0, Nav. Res. Lab. Rep. NRL/FR/7322-00-9962, 42 pp., Nav. Res. Lab., Stennis Space Cent., MS.

Nitani, H., 1972: Beginning of the Kuroshio. Pp. 353-369 in The Kuroshio, H. Stommel and K. Yoshida, eds. University of Tokyo Press, Tokyo, Japan.

Price, J. F., 1983: Internal wave wake of moving storm. Part I, Scales, energy budget and Observations, *J. Phys. Oceanography*, **13**, 949-965.

Price, J. F., T. B. Sanford, and G. Forristall, 1994: Observations and simulations of the forced Response to moving hurricanes. *J. Phys. Oceanography*, **24**, 233-260.

Shay, L. K. and E. W. Uhlhorn, in press : Loop current response to Hurricanes Isidore and Lili. Mon. Wea. Rev.